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# ON THE INFLUENCES OF CHANGES OF CARRIER DENSITY ON THE CURRENT FLOW IN A CHANNEL

by

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Lee Evans



September 1965



U. S. ARMY MATERIEL COMMAND
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ABERDEEN PROVING GROUND, MARYLAND

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A B E R D E E N  P R O V I N G  G R O U N D,  M A R Y L A N D

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KAPullen,Jr./LEvans/blw
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## ABSTRACT

A study is made of the effect of varying the density of free charge carriers in a semiconductor channel under the influence of a retarding field. It is found that the conditions required for charge binding in the space-charge region are dramatically altered by changes in the distrubution of charge. The transconductance per unit current is also drastically altered. Based on the study, it can be presumed that significantly more efficient field effect transistors can be built than have been obtained to date.

TABLE OF CONTENTS

TABLE OF SYMBOLS

| | |
|---|---|
| $a$ | half-width of channel |
| $a_j$ | coefficient in power series |
| $b$ | half-width of conducting section of channel |
| $e_o$ | dielectric permittivity of free space |
| $E_y$ | y component of electric field |
| $g_m$ | transconductance |
| $g_m/I$ | transconductance per unit current |
| $j_k$ | exponent in power series |
| $k$ | Boltzmann's constant |
| $K$ | dielectric constant of space-charge region |
| $K$ | $\kappa e_o$ |
| $K_{Ge}$ | value of K for germanium |
| $K_{Si}$ | value of K for silicon |
| $L$ | length of channel in direction of current flow |
| $n$ | exponent on y |
| $N_{ag}$ | number of acceptors in gate |
| $N_a(y)$ | number of acceptors as a function of y in channel |
| $N_{dg}$ | number of donors in gate |
| $N_d(y)$ | number of doners as a function of y in channel |
| $p$ | charge density in channel at $y > b + \Delta$ (a small increment) |
| $p_h$ | maximum charge density for modified catenary distribution |
| $p_{n+}$ | charge density in n+ region |
| $p_o$ | charge density constant, in arbitrary units |
| $p(y)$ | charge density in channel |
| $p_\alpha$ | maximum charge density for inverted parabola distribution |
| $p_\tau$ | total available mobile charge density |

TABLE OF SYMBOLS (Contd)

| | |
|---|---|
| $q$ | charge on electron |
| $T$ | absolute temperature |
| $V$ | potential difference |
| $V_y$ | potential difference from the point y = y to y = a(= 1) |
| $W$ | potential across the space-charge region |
| $W_o$ | value of W for b = 0 |
| $x$ | coordinate at right-angles to y and L |
| $y$ | transverse coordinate in channel (toward gate from center) |
| $z$ | direction of source-to-drain field |
| $\Delta$ | infinitessimal |
| $\Lambda$ | Fermi constant |
| $\mu$ | mobility |
| $\sigma(y)$ | conductivity |

## INTRODUCTION

The behavior of the channel for the field-effect, or unipolar, transistor has been treated in some detail in many recent papers*, and generally is consequently rather well understood. In fact, it appeared until recently that the general limitations predicted theoretically were complied with, and that as a consequence, no further analytical study would be required.

A new limiting condition applying to these devices has recently been found by the authors. This makes necessary a reconsideration of certain aspects of the theory of channel behavior. This limitation is a transconductance-per-unit-current limitation of the kind encountered with both bipolar transistors and electron tubes. It was not predicted by earlier theory, which showed a power-law relationship between transconductance and current.

The transconductance-per-unit-current limit is the same one that is encountered with bipolar transistors, namely, 39,000 micromhos per milliampere. It occurs at very small values of channel current, values less than a microampere in general, and may exist for several orders of magnitude of current.

There is also a philosophical difficulty associated with the concept of pinchoff as it is applied to these devices. Strictly, pinchoff in the precise meaning of the term would be a condition of total cutoff, or a reduction of the channel current to zero value, or at most the uncontrollable leakage current. The word pinchoff as normally applied with these devices is a dynamical kind of limitation in that a condition is reached in which an increase of source-to-drain voltage results in almost no change of current, or a condition of near-infinite dynamic impedance develops.

This behavior is what one might call a "saturated channel" effect, in that over a range of applied voltage, a certain number of charges could diffuse through a gate area, and the magnitude of the voltage

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* *A bibliography is presented on page 24 of this report.*

applied on the drain or collector then would be relatively unimportant. Such a condition could develop if the collection field swept out the carriers at the exit end of the channel through the gate region, and the process of getting through the gate region then was one of diffusion.

With such a situation, as the gate bias is increased to limit the channel size, a point could be reached at which the gates might make contact, and conduction in limited amount might continue through tunneling. Under such conditions, the operation of the transistor might approximate that of a conventional bipolar transistor, with the gate region forming an incipient base region. The conventional transconductance limitation applicable to bipolar transistors could be expected to apply. It is the purpose of this paper to re-examine the conventional theory for field-effect devices to see how it can be used as a basis for a more rigorous explanation of the effects as observed.

## THEORY

The discussion to follow is based on, and parallels closely up to a point, the study presented by Shockley in his paper "A Unipolar 'Field-Effect' Transistor", published in the November 1952 issue of the Proceedings of the I. R. E. First the theory of the channel as given there is reviewed briefly, and then a further analytical look is taken at some of the relations given to see how they might be modified to clarify ideas on device behavior. It will become evident from these relations that the nominal transconductance efficiency can readily be changed by some changes in the characteristics built into the channel.

If one takes the structure of the field-effect device to be essentially as given by Shockley in Figure 1 (his Figure 1, also), it is clear that a channel exists which is widened and narrowed through the space-charge action by the n+ gate regions, and a current flow from the source to the drain will be influenced by the widths of the space-charge regions.

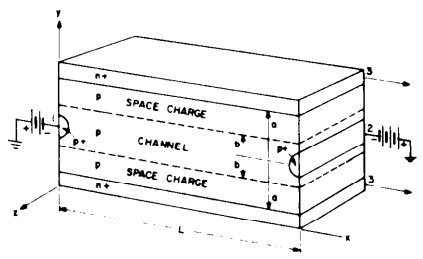

FIG. 1 - SPACE-CHARGE REGION AND CHANNEL IN A (n+) p (n+) STRUCTURE

Generally, the assumption is made that the magnitude of the reverse bias across the semiconductor juntion as seen from source to gate and from drain to gate are approximately the same, at least in the initial stages of the calculation. This assumption assures approximate parallelism of the two sides of the channel, a situation which cannot be exactly true in practice. Such an assumption is convenient for an initial approximation, however. It is also assumed that the doping in the gate layers, marked n+, is large compared to that in the channel. For our approximation, this is assumed to be true, but for more precise determination, some alterations in the calculation might be required. Based on the definitions listed in the Table of Symbols, the charge densities in the p and n+ regions are:

$$p(y) = q[N_a(y) - N_d(y)] \quad \text{in the p-region} \tag{1a}$$

$$p_n = q(N_{dg} - N_{ag}) \quad \text{in the n+-region} \tag{1b}$$

where q is the charge on the electron, and the various N's are the numbers of the donor and acceptor centers in the respective layers. Clearly, only part of the p-region may be assumed to be a conducting channel, as the charge carriers in the space-charge region are essentially bound by the potential applied to the gate.

Hence, the density of the holes in the central region of the channel is a function of the carrier density, and the conductivity may be written in terms of the number and the mobility in the equation:

$$\sigma(y) = \mu p(y) \tag{2}$$

where $\mu$ is the mobility of the holes.

The charge distribution in the space-charge region on either side of the channel is assumed to be symmetrical about the point y = 0 through the source and the drain terminals. In the simple case considered by Shockley, the density is constant and negative within the space-charge region, and practically constant, positive, and very much larger within

the terminal, or n+, region. In practice, of course, neither of these is truly constant, but both may be idealized to satisfy some chosen arbitrary form, such as the constant values chosen by Shockley.

Because of the necessary existance of charge equality across the barrier in a bound-charge, or space-charge, region, it is to be noted that the total charge within the space-charge region must equal that collected opposite it in the n+ or gate region. Otherwise, there will be a net electric field.

The nature of the electric field in the space-charge region may be approximated by the application of Poisson's equation to the one-dimensional distribution which is obtained by considering the structure to be a section of an infinite structure in the "z" coordinate, and assuming that within the region where $0 < x < L$ the field is independent of the coordinate x. This condition is postulated by the assumption that the source-to-gate diode voltage is substantially equal to the drain-to-gate voltage. The resulting equation is:

$$\kappa\epsilon_o d^2V/dy^2 = - \kappa\epsilon_c dE_y/dy = - p(y) \qquad (3)$$

where p(y) is, as before, the charge density as a function of the coordinate y.

Near the point y = b, the space, or bound, charge changes from a value of zero with y just less than b to a value equal to $- p_b$ for y just greater than b. Shockley points out that this transition region is about one "Debye Length" thick, and that in it, the potential across the barrier changes by the Fermi potential, or $kT/q = \Lambda^{-1}$ where k is Boltzmann's constant, and T is the absolute temperature. Understandably, the "Debye Length" must be small compared to the lengths, a, b, and L, and the Fermi potential must be small compared to the junction potential, W, and accordingly may be neglected in comparison. As a consequence of these relations we have:

$$E_y = 0 \qquad \text{at} \qquad y = b \tag{4}$$

$$dE_y/dy = - p/\kappa e_o = - p(y)/\kappa e_o; \qquad y > b \ . \tag{5}$$

Now, in the case where the charge density is uniform, Equation (5) may be integrated to give:

$$E_y = - p_o(y - b)/\kappa e_o \ . \tag{6}$$

In this instance, the magnitude of the electric field increases linearly across the space-charge region, and decreases back to zero across the n+ semiconductor material for the terminal of the junction.

The potential difference between any point within the space-charge and the boundary of the gate terminal may also be determined through the use of a definite integral, or strictly a pair of definite integrals, one over the space-charge region, and the other over the n+ region. Because of the relatively high charge density in the n+ region and its relative thinness, the potential difference is primarily that across the space-charge, or p, region. The general integral takes the form:

$$V = - \int_y^a E_y dy \tag{7}$$

When the charge throughout the region is uniformly distributed, Equation (7) simplifies to the form:

$$V = - (p_o/2K)[(y - b)^2 - (a - b)^2] \tag{8}$$

where K, the dielectric constant, has the value $\kappa e_o$, and is measured normally in farads per meter in the mks system. For the problem at hand; it can be equally well taken in terms of farads per centimeter by using mobilities in $cm^2$ per volt-second, and conductivities in ohms per centimeter. Typical values of $\kappa$ of 16 and 12 respectively for germanium and silicon lead to the values of K for germanium and silicon of:

$$K_{Ge} = 1.42 \times 10^{-12} \text{ farads per centimeter} \tag{9}$$

$$K_{Si} = 1.06 \times 10^{-12} \text{ farads per centimeter} \ . \tag{10}$$

In terms of the previous equations and relations, the potential which will exist in the channel is:

$$V = - \int_b^a E_y dy \quad . \tag{11}$$

For the uniform-charge case, this leads to the potential on the edge of the active channel as:

$$W = - V(b) = [1 - (b/a)]^2 W_o \tag{12}$$

where the value of $W_o$ is given by:

$$W_o = p_o a^2/2K \quad . \tag{13}$$

Clearly, the value of $W_o$ is the voltage required to yield a minimum value of y, or b, equal to zero, or the voltage required just to "close" the channel.

Actually, the problem which really concerns us is the determination of how to minimize the total voltage required to "close" the channel for a given maximum current carrying capacity. For this reason, it is important to restudy the simplified problem to attempt to find the form which p(y) should take in order to assure that the value of the integral, Equation (11), will be as small as possible subject to the integral:

$$p_T = \int_0^a p(y) dy \quad . \tag{14}$$

For simplification of calculations, we now take the value of a as unity.

Superficially, the problem of minimizing the voltage would appear to be one in the calculus of variations, and it should be examined to see if there is in fact a minimum, and if there is not, under what conditions the general form can be led toward a minimum value subject to construction limitations*. In addition, it is of interest to examine the variation of the width of the space-charge region with the applied potential across it.

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* *Dr. C. Masaitis of the Ballistic Research Laboratories has pointed out to the authors that a tractible variational problem probably does not exist. This is also the implication of the manner of variation to be noted as a function of n.*

The first step in the study of the relation of channel characteristics to the potential gradient across the space-charge region is to determine the basic general forms for the equations for the channel current and the space-charge voltage expressed in terms which can be related to channel theory. The same basis equations which have been used above are again applicable, with the only difference being a somewhat greater complexity in the expressions.

Let it be assumed for an initial consideration that the expression for the charge in the channel takes the form:

$$p = p_n y^n \tag{15}$$

where the value of $p_n$ is such that the total integrated charge within the entire channel region will be $p_\tau$. In each case, $p_\tau$ is the density of the charges corresponding to the channel under consideration but for a channel having a constant charge density, that is, with $n = 0$. The range for the values of y is $0 \leq y \leq 1$.

Equality of maximum total conduction (the full-on condition) for the channel requires that the integral of available carriers across the channel for each configuration be the same, and in each case, this total is taken to be $p_\tau$. Setting up the basic integral on the assumption that $p = p_n y^n$, one obtains:

$$p_\tau = \int_0^1 p_n y^n dy = p_n/(n + 1) \ . \tag{16}$$

Clearly, the value required for $p_n$ is $(n + 1)p_\tau$. Substituting in the basic differential equation, one gets:

$$dE_y/dy = - p_n y^n/K \ . \tag{17}$$

Integrating between the limits zero and y gives:

$$E_y = - (1/K)p_n \int_0^y y^n dy = - [1/K(n + 1)]p_n [y^{n+1}]\Big|_0^y \ . \tag{18}$$

Substituting for $p_n$ and inserting the limits gives:

$$E_y = - (p_T/K)y^{n+1} \quad . \tag{19}$$

This equation may be integrated once more to determine the voltage required to bind the charge in the space-charge region. The limits in this instance are from y to unity instead of from zero to y:

$$V_y = - (p_T/K) \int_y^1 y^{n+1} dy \quad . \tag{20}$$

Integrating gives:

$$V_y = - [p_T/K(n + 2)]y^{n+2} \Big|_y^1 = [p_T/K(n + 2)][1 - y^{n+2}] \quad . \tag{21}$$

It is evident from this equation that the voltage changes very little for values of y near zero and values of n greater than three or four. Since the overall value of $V_y$ across the channel takes the form:

$$V_o = p_T/K(n + 2) \tag{22}$$

it is evident that the total voltage required to bind the charge is inversely proportional to (n + 2), or the required voltage decreases rapidly with an increase of exponent. A set of curves showing the variation of V with y for different values of the exponent are shown in Figure 2.

The transconductance per unit current for active devices is one of the more important parameters first because solid-state devices are subject to a limitation in terms of this parameter (the Fermi constant), and second because this parameter tends to indicate the relative efficiency of such devices. For this reason, the equation defining the parameter is now derived.

It is not possible to make the differentiation to determine dI/dV directly inasmuch as both the current and the voltage are functions of the variable y, and often it is difficult to convert functions of this kind into explicit form for direct differentiation. Fortunately,

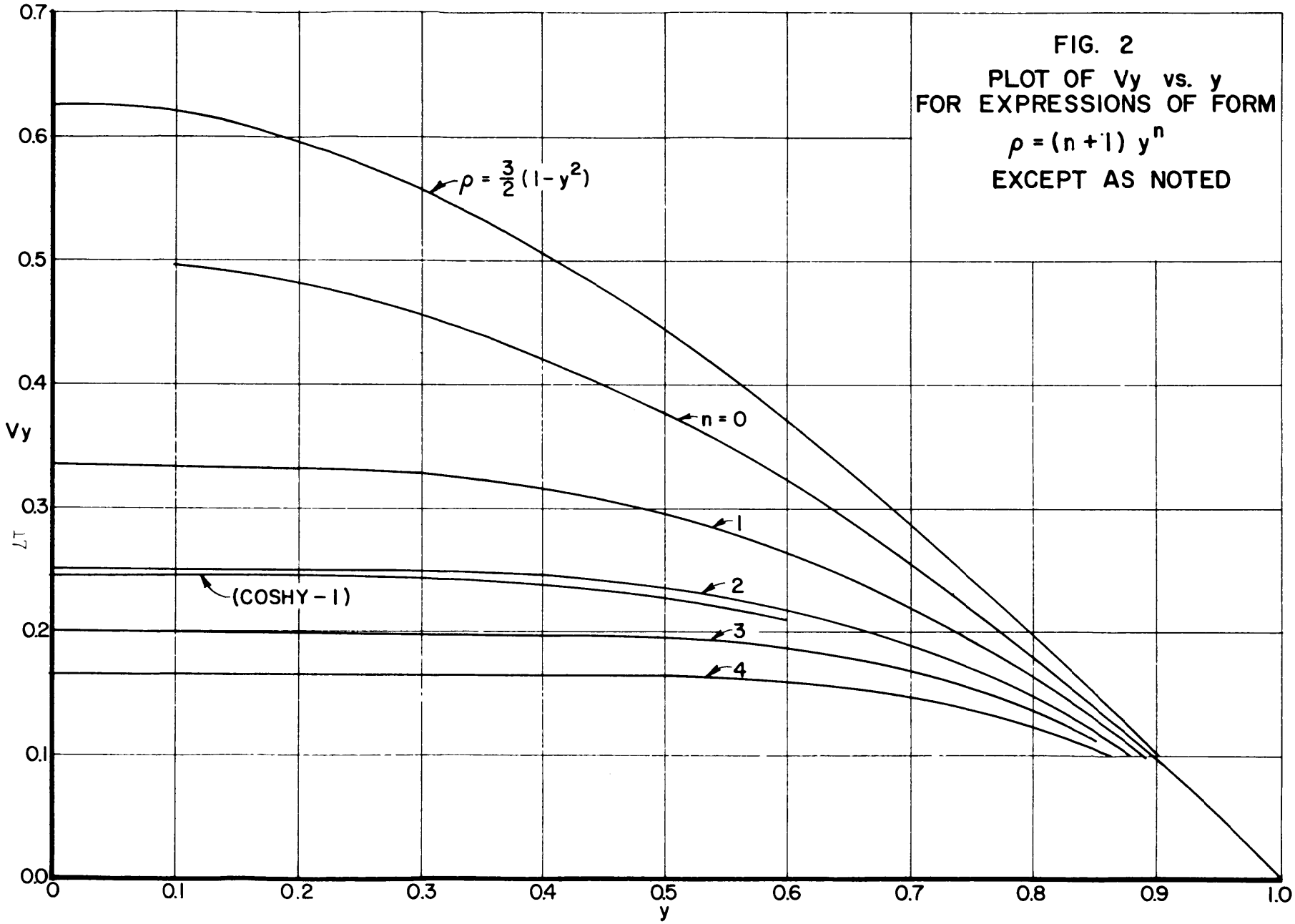
FIG. 2
PLOT OF Vy vs. y
FOR EXPRESSIONS OF FORM
$\rho = (n+1)\, y^n$
EXCEPT AS NOTED
$\rho = \frac{3}{2}(1-y^2)$
n = 0
1
2
3
4
(COSHY - 1)
Vy
y
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

however, the derivative may be found by taking the partial derivative of both the function for I and the function for V with respect to the variable y, and the quotient gives the appropriate derivative.

The current flow in the channel is proportional to the number of unbound charges available as a function of y within the channel:

$$I = \mu \int_0^y p_n y^n dy = \mu p_n y^{n+1}/(n + 1) \Big|_0^y = \mu p_T y^{n+1} \qquad (23)$$

where, as before, the mu is the mobility of the carriers. Since this integral is taken from zero to the variable as the upper limit, its derivative takes the form:

$$dI/dy = \mu p_n y^n = \mu(n + 1)p_T y^n \quad . \qquad (24)$$

Also, the ratio dI/Idy is given by the equation:

$$dI/Idy = (n + 1)/y \quad . \qquad (25)$$

Differentiating Equation (21) with respect to y gives the result:

$$dV_y/dy = - (p_T/K)y^{n+1} \quad . \qquad (26)$$

Dividing Equation (24) by Equation (25) then gives:

$$g_m/I = (dI/dy)/I(dV_y/dy) = - K(n + 1)/p_T y^{n+2} \quad . \qquad (27)$$

This is essentially the equation, contours for which are plotted in Figure 3. In the plots, the constants K and $p_T$ have been taken to have a ratio of unity, and different values of n are used as the plotting contour. It is interesting to note that the transconductance per unit current increases directly as the exponent n is increased as long as the value of y is significantly less than unity.

In order to determine how these results might compare with results expected in typical kinds of structures, it is interesting to compute both the voltage curve and the transconductance-per-unit-current curve under the assumption that the charge distribution has the form

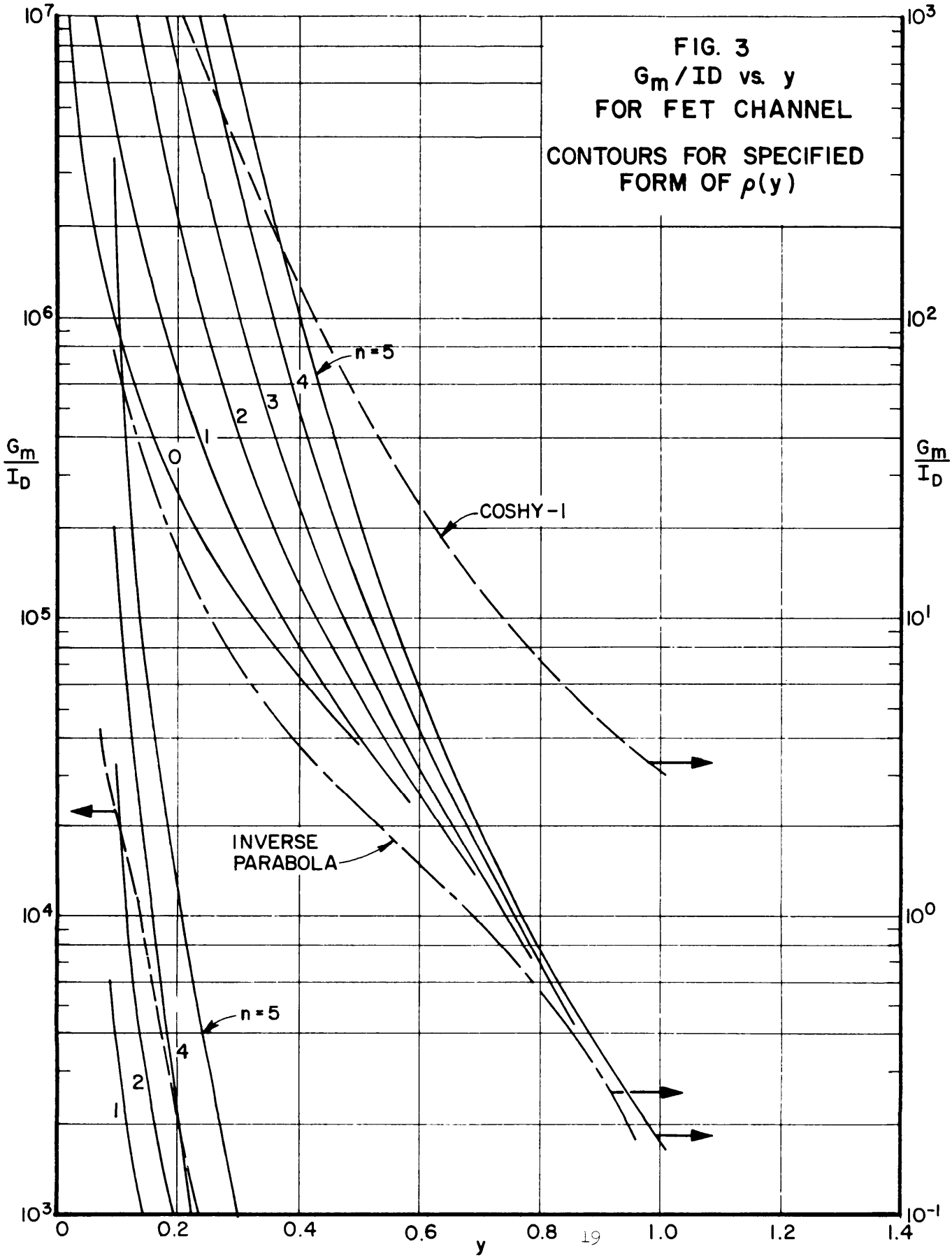
FIG. 3
$G_m/ID$ vs. y
FOR FET CHANNEL
CONTOURS FOR SPECIFIED
FORM OF $\rho(y)$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$\frac{G_m}{I_D}$
$\frac{G_m}{I_D}$
n=5
4
3
2
1
0
COSHY-1
INVERSE
PARABOLA
n=5
4
2
1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
y

$p = p_\alpha(1 - y^2)$. (This probably gives the carrier distribution most nearly like that which is obtained with ordinary devices. In any case, the representation normally will be between that given by this relation and the above relation (Equation 15) with n = 0.) In this instance, the total charge over the channel is found to be:

$$p_T = p_\alpha \int_0^1 (1 - y^2)dy = p_\alpha(y - y^3/3) \Big|_0^1 = 2p_\alpha/3 \quad . \tag{28}$$

The equation for the channel current takes the form:

$$I = (3p_T\mu/2) \int_0^y (1 - y^2)dy = (p_T\mu/2)[3y - y^3] \quad . \tag{29}$$

As before, the derivative of I with respect to y removes the integral sign.

The voltage across the space-charge region is obtained from the integral:

$$V(y) = - (p_T/2K) \int_y^1 [3y - y^3]dy = - (p_T/4K)[3y^2 - y^4/2] \Big|_y^1 \quad . \tag{30}$$

Once again, taking the ratio of $p_T$ to K to be unity, a curve expressing V as a function of y may be plotted as in Figure 2.

Now, the transconductance per unit current may be obtained by differentiation and division. The resulting equation for this charge distribution is:

$$g_m/I = - 6K(1 - y^2)/[p_T(3y - y^3)^2] \quad . \tag{31}$$

This equation has also been plotted on Figure 3 subject to the condition that the ratio of $p_T$ to K have a value unity.

Another possible distribution worthy of examination is a modified hyperbollic cosine function in the form:

$$p = p_h[\cosh y - 1] \quad . \tag{32}$$

The value of $p_h$ in terms of $p_T$ is then given by the equation:

$$p_\tau = p_h \int_0^1 (\cosh y - 1)dy = p_h(\sinh y - y)\Big|_0^1 = 0.175\, p_h \ . \quad (33)$$

The general equation for the channel current is:

$$I = \mu \int_0^y 5.714(\cosh y - 1)dy = 5.714\mu(\sinh y - y) \ . \quad (34)$$

The ratio of dI/dy to I then is:

$$dI/Idy = (\cosh y - 1)/(\sinh y - y) \ . \quad (35)$$

The binding voltage in the space-charge region is given by:

$$V(y) = -(5.714p_\tau/K) \int_y^1 (\sinh y - y)dy$$

$$= (5.714p_\tau/K)[\cosh y - y^2/2]\Big|_y^1 \ . \quad (36)$$

The voltage curve is plotted in Figure 2.

By differentiation, as before, the value of dV/dy is:

$$dV/dy = (5.714p_\tau/K)(\sinh y - y) \quad (37)$$

and the transconductance per unit current is given by:

$$g_m/I = 0.175K(\cosh y - 1)/[p_\tau(\sinh y - y)^2] \ . \quad (38)$$

This curve is also plotted in Figure 3.

In reality, of course, it is not possible to obtain charge distributions which fit any of the above considered forms. For this reason, it is desirable to establish the representation in terms of a power-series expansion, and to perform the analysis based on the power series. The handling of the problem can be simplified by taking the power series in the form:

$$p = p_o\left[1 + \sum_j^n a_j y^j\right] \ . \quad (39)$$

In the instance, the value of $p_T$ takes the form:

$$p_T = p_o \int_0^1 (1 + \sum a_j y^j)dy = p_o\left[1 + \sum (a_j y^{j+1}/(j + 1))\right]\Big|_0^1$$

$$= p_o\left[1 + \sum (a_j/(j + 1))\right] \quad . \tag{40}$$

This equation may be solved for $p_o$ and substituted into Equation (39).

Since as before the current flow is proportional to the integral in Equation (40), but with the limits from 0 to y, the value of dI/dy and I are readily shown to be:

$$I = \mu p_T\left[1 + \sum (a_j y^{j+1}/(j + 1))\right]/\left[1 + \sum (a_j/(j + 1))\right] \quad , \tag{41}$$

$$dI/dy = up_T\left[1 + \sum (a_j y^j)\right]/\left[1 + \sum (a_j/(j + L))\right] \quad . \tag{42}$$

The quotient of these two equations gives:

$$dI/Idy = \left[1 + \sum (a_j y^j)\right]/\left[1 + \sum (a_j y^{j+1}/(j + 1))\right] \quad . \tag{43}$$

In a similar manner, the equation for the binding voltage may be determined:

$$V = -(p_o/K) \int_y^1 \left[1 + \sum (a_j y^{j+1}/(j + 1))\right]dy$$

$$= -(p_o/K)\left[1 + \sum (a_j y^{j+2}/(j + 1)(j + 2)\right]\Big|_y^1 \tag{44}$$

where the value of $p_o$ again may be found from Equation (40). This equation may be used directly if the value of the voltage is required, or it may be differentiated to give dV/dy for the problem at hand. When this is done, the result is:

$$dV/dy = p_o\left[1 + \sum (a_j y^{j+1}/(j+1))\right]/K$$

$$= p_\tau\left[1 + \sum (a_j y^{j+1}/(j+1))\right]/K\left[1 + \sum (a_j/(j+1))\right] . \quad (45)$$

As a result, the transconductance per unit current is given by the equation:

$$g_m/I = K\left[1 + \sum (a_j y^j)\right]\left[1 + \sum (a_j/(j+1))\right]\Big/$$

$$p_\tau\left[1 + \sum (a_j y^{j+1}/(j+1))\right]^2 . \quad (46)$$

This equation gives, in terms of power expansions, the transconductance per unit current which may be expected based on the given channel charge distribution.

## CONCLUSIONS

It is shown that the distribution of charge within the channel for a field-effect transistor has a profound effect on its behavior. Both the total potential difference required to switch the channel from fully conducting to completely off, and the transconductance per unit current are shown to be strongly dependent on the distribution of charge within the channel. In fact, both of these characteristics are improved through the use of doping profiles of the form

$$p = p_\beta y^n \quad (47)$$

where the value of n is positive and significantly greater than unity, as large as possible, in fact.

KEATS A. PULLEN, JR. LEE EVANS

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## APPENDIX

## CALCULATION TABLES

### TABLE I

VALUES OF POTENTIAL AS A FUNCTION OF y AND n

| y/n | 0 | 1 | 2 | 3 | 4 | Para | Cosh |
|---|---|---|---|---|---|---|---|
| 0.0 | 0.50 | 0.33 | 0.25 | 0.20 | 0.17 | 0.62 | 0.25 |
| 0.1 | 0.50 | 0.33 | 0.25 | 0.20 | 0.17 | 0.62 | 0.25 |
| 0.2 | 0.48 | 0.33 | 0.25 | 0.20 | 0.27 | 0.60 | 0.25 |
| 0.3 | 0.46 | 0.33 | 0.25 | 0.20 | 0.17 | 0.56 | 0.24 |
| 0.4 | 0.42 | 0.31 | 0.24 | 0.20 | 0.17 | 0.51 | 0.24 |
| 0.5 | 0.38 | 0.29 | 0.23 | 0.19 | 0.16 | 0.44 | 0.23 |
| 0.6 | 0.32 | 0.26 | 0.22 | 0.18 | 0.16 | 0.37 | 0.22 |
| 0.7 | 0.26 | 0.22 | 0.19 | 0.16 | 0.15 | 0.28 | 0.19 |
| 0.8 | 0.18 | 0.16 | 0.15 | 0.13 | 0.12 | 0.20 | 0.15 |
| 0.9 | 0.10 | 0.09 | 0.09 | 0.09 | 0.08 | 0.10 | 0.09 |
| 1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

### TABLE II

VALUES OF $g_m/I$ AS A FUNCTION OF y AND n

| y/n | 0 | 1 | 2 | 3 | 4 | Para | Cosh |
|---|---|---|---|---|---|---|---|
| 0.0 | $\infty$ | $\infty$ | $\infty$ | $\infty$ | $\infty$ | $\infty$ | $\infty$ |
| 0.1 | 100 | 500 | 3300 | 25000 | $2 \times 10^5$ | 66.3 | 21900 |
| 0.2 | 25 | 62.5 | 208 | 780 | 3100 | 16.3 | 2060 |
| 0.3 | 11.1 | 18 | 41 | 103 | 270 | 7.12 | 389 |
| 0.4 | 6.2 | 7.8 | 13 | 24 | 49 | 3.84 | 121 |
| 0.5 | 4.0 | 4.0 | 5.3 | 8.0 | 12.8 | 2.40 | 50.2 |
| 0.6 | 2.8 | 2.3 | 2.6 | 3.2 | 4.2 | 1.52 | 24 |
| 0.7 | 2.04 | 1.5 | 1.4 | 1.5 | 1.7 | 0.96 | 13 |
| 0.8 | 1.56 | 0.97 | 0.81 | 0.76 | 0.76 | 0.59 | 7.6 |
| 0.9 | 1.23 | 0.69 | 0.57 | 0.42 | 0.37 | 0.30 | 4.7 |
| 1.0 | 1.00 | 0.80 | 0.33 | 0.25 | 0.20 | 0.00 | 3.1 |

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| Channel saturation | Field-effect transistor |
| Channel theory | Poisson's equation |
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ON THE INFLUENCE OF CHANGES OF CARRIER DENSITY ON THE CURRENT FLOW IN A CHANNEL By K. A. Pullen, Jr., BRL; Lee Evans, Siliconix. DDC; OTS. RDT&E No. 1L013001A91A September 196

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| Binding potential | Doping variations |
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| Channel theory | Poisson's equation |
| Charge binding | Transconductance per unit current |
| Charge distribution | Unipolar transistor |

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13. ABSTRACT

A study is made of the effect of varying the density of free charge carriers in a semiconductor channel under the influence of a retarding field. It is found that the conditions required for charge binding in the space-charge region are dramatically altered by changes in the distribution of charge. The trans-conductance per unit current is also drastically altered. Based on the study, it can be presumed that significantly more efficient field effect transistors can be built than have been obtained to date.

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